# DIGITAL TECHNOLOGY

14





## 14.1 (SL OPTION C.1) ANALOGUE AND DIGITAL SIGNALS

14.1.1 Solve problems involving the conversion between binary numbers and decimal numbers.

14.1.2 Describe different means of storage of information in both analogue and digital forms.

14.1.3 Explain how interference of light is used to recover information stored on a CD.

14.1.4 Calculate an appropriate depth for a pit from the wavelength of the laser light.



### 14.1.1 (C.1.1) BINARY AND DECIMAL

When we write down a number such as 236, we are actually using a short hand notation and also assuming that the number is to the base 10. In base 10, the short hand 236 actually means $2 \times 10^2 + 3 \times 10^1 + 6 \times 10^0$ i.e. 200 + 30 + 6. If the number where to the base 7, then 236 would mean $2 \times 7^2 + 3 \times 7^1 + 6 \times 7^0 = 98 + 21 + 6 = 125$ in decimal.

So, numbers can be to any base, the simplest, and perhaps the most important, being base 2, or the **binary system** as it is often called. The reason why it is so important is that it forms the basis of all modern information technology. And why? Because the simplest electronic device is a switch and a switch is either OFF (binary 0) or ON (binary 1). In effect, the central processing chip of your computer consists of millions of transistors acting as electronic switches.

So if computers work with binary numbers and we work with decimal numbers, we need to be able to covert decimal to binary and vice versa.

Converting from decimal to binary is a little tedious. Essentially, you have to find the largest power of 2 that is less than the decimal number and then subtract and keep repeating this until you reach $2^0$, putting a 1 for the first zero value reached then zero's for the powers of 2 that are left We can see how this works for the number 236 by looking at Table 1401.

| power of 2 | $2^7$ | $2^6$ | $2^5$ | $2^4$ | $2^3$ | $2^2$ | $2^1$ | $2^0$ |
|---|---|---|---|---|---|---|---|---|
| subtractions | 128 | 64 | 32 | 16 | 8 | 4 | 2 | 1 |
| denary number left | 108 | 44 | 12 | 12 | 4 | 1 | 0 | 0 |
| binary | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 0 |

*Figure 1401 Converting from binary to decimal*

The conversion therefore gives 236 in binary as 11101000

$= 1 \times 2^7 + 1 \times 2^6 + 1 \times 2^5 + 0 \times 2^4 + 1 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 0 \times 2^0$

$= 128 + 64 + 32 + 8 + 4 = 236.$

Clearly, as seen from this example, converting binary into denary is a lot simpler. To emphasise the point the binary number 10011 = $1 \times 2^4 + 0 \times 2^3 + 0 \times 2^2 + 1 \times 2^1 + 1 \times 2^0$

= 16 + 2 + 1 = 19.

*NB. In the IB examination problems will be limited to 5 digit binary numbers.*

Exercise

1. Convert the decimal numbers 15 and 62 to binary.

2. Convert 1000011 to decimal.

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## Least significant bit (LSB) and most significant bit (MSB)

In any binary number the last digit on the left of the number is referred to as the **least significant bit** (LSB) and essentially determines whether the decimal number is odd or even.

The **most significant bit** (MSB) on the other hand is the first digit on the left of a binary number.

For example, if we consider the binary number 11010, the LSB is 0 and the MSB is 1. The MSB is therefore a 5-bit binary number of value 16.

The least significant bits have the useful property of changing rapidly if the number changes even slightly. For example, if 2 (binary 00000010 ) is added to 3 (binary 00000011), the result will be 5 (binary 00000101) and three of the least significant bits will change (010 to 101). By contrast, the three most significant bits stay unchanged (000 to 000).

*A word of warning.* In some literature the abbreviations LSB and MSB stand for least significant byte and most significant byte respectively. For bits, the abbreviations are lsb and msb. A byte is just a binary number so, for example LSB would refer to the least significant number in an array of numbers.

## 14.1.2 (C.1.2) INFORMATION STORAGE

Essentially information may be represented in two forms, analogue and digital.

**Analogue information** varies continuously and can have an infinite number of values. For example, the length of the mercury column in a mercury-in-glass thermometer varies continuously and although you might read the temperature as 18 °C, it could be 18.324556791 °C. On the other hand, the information conveyed by a two colour traffic signals is digital, that is, the signal is either red or green.

If information is to be stored, then it can also be stored in analogue or **digital** form. For example, personal information such as name, address, age might be stored as written information on a card index (analogue) or as a series of punched holes on a paper tape (digital). Such information can also be stored electronically on magnetic tape (analogue) or on a **digital versatile (video) disc**, DVD, (digital). Music or speech is stored on a long-playing record (LP) in analogue form and on a **compact disc** (CD) in digital form. Clearly in the world of today, most information is stored electronically and in digital form and it this that this topic looks at in more detail.

We can understand how an analogue voltage signal can be encoded as a digital signal by looking at the following example.

Suppose the amplitude of the analogue voltage is 6.0 V. Our 'digital storage device' has a clock reference system as shown in Figure 1402. The 6.0 V voltage is then encoded as the binary pulse 0110.

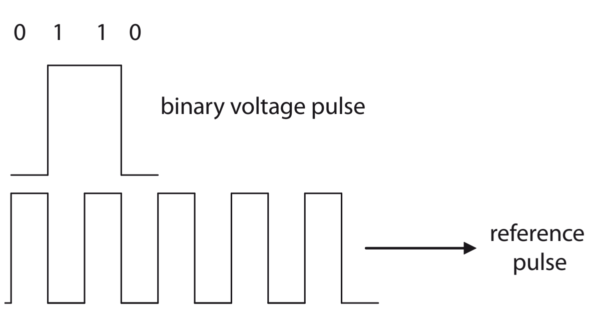


*Figure 1402 A binary pulse*

If a microphone is attached to an oscilloscope and you sing into the microphone then the sound of your voice is converted into an analogue voltage signal that will be shown displayed on the screen of the oscilloscope. We can now see from Figure 1402, the principle behind converting your voice into a digital signal.

## 14.1.3,4 (C.1.3,4) The CD

The essential structure of CD is shown in Figure 1403 (a).

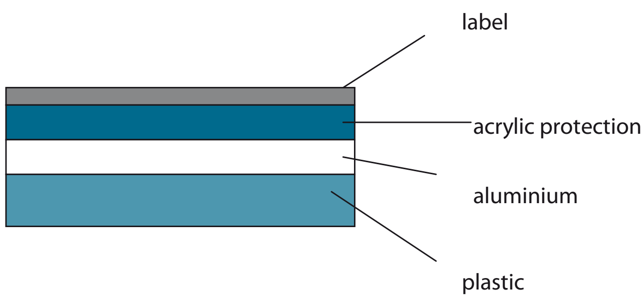


*Figure 1403 (a) CD structure*

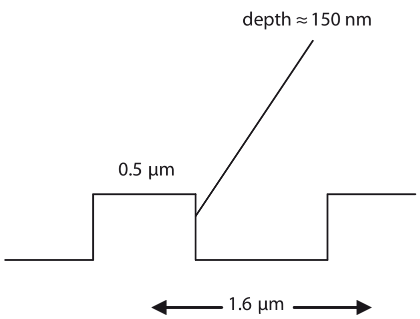


*Figure 1403 (b) CD micro-structure*

Information is encoded onto the surface of the aluminium as a series of "bumps" and flats. The bumps represent a binary zero and the flats a binary 1. The dimensions of the bumps and flats are very small indeed, about 0.5 µm wide, 0.83 µm long and about 150 nm deep. The bumps and flats are arranged along tracks which are separated by about 1.6 µm as is shown in Figure 1402 (b). It is this that enables such a great deal of data to be stored in such a relatively small area. To "read" the data, light from a laser is shone onto the aluminium. The bumps appear as pits on the aluminium side, but on the side that the laser reads, they are indeed bumps. For this reason you will often come across the term "pit" with reference to CDs and DVDs.

The laser light reflected from the flat will be read as a binary one. However, if the depth of the bumps and the wavelength of the light is just right, light reflected from the edge of the bump and the flat will interfere destructively and the absence of reflected light will be read as a zero. We can illustrate this by means of the following example.

Example

Laser light of wavelength 780 nm is used to read the data stored on a CD. Calculate the minimum height of the bumps (depth of the pits) that must be etched onto the CD in order that the stored data can be read.

Solution

The light reflected from the flat, that is the bottom of the pit created by the bumps, travels a distance 2d further to the receiver than the light reflected from the bump.

For destructive interference the path difference between the light equals $\frac{\lambda}{2}$.

Hence $d = \frac{\lambda}{4} = \frac{780}{4} = 195$ nm.

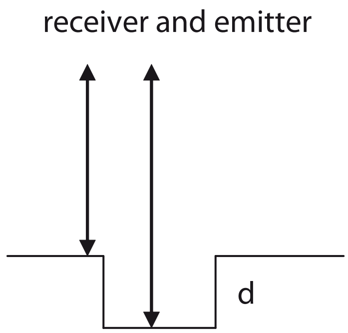


*Figure 1404 How a laser reads a CD*

The essential difference between a CD and a DVD is in terms of the amount of data that they can store. Typically a CD can store 650 MB and a DVD 4.7 GB. The reason for this is that in a DVD the pits are 0.44 µm in diameter and the tracks are only 0.74 µm apart.

The laser light used to read data from a CD or DVD is focussed by a lens onto the pits and flats. The lens acts as a circular aperture and produces a diffraction pattern on the disk. If more than one pit falls inside the central maxima of the diffraction pattern, the pits cannot be resolved and information is lost. The Raleigh criterion (see 11.4) gives the condition for resolution namely

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$$\theta = 1.22\frac{\lambda}{b}$$

where $b$ is the diameter of the lens.

If $d$ is the distance of the focussing lens from the CD surface and $r$ is the radius of the principal maximum of the diffraction pattern formed on the surface, then

$$\frac{r}{d} = 1.22\frac{\lambda}{b}$$

Since for a DVD $r$ is smaller than that for a CD, the above equation shows that the wavelength of the laser light used to read the data must be less than that used for a CD. (Provided all other quantities remain constant).

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14.1.5 Solve problems on CDs and DVDs related to data storage capacity.

14.1.6 Discuss the advantage of the storage of information in digital rather than analogue form.

14.1.7 Discuss the implications for society of ever-increasing capability of data storage.



## 14.1.5 (C.1.5) SOLVE PROBLEMS ON CDS AND DVDS RELATED TO DATA STORAGE CAPACITY

Exercises

1. A typical wavelength of light used to read data from a CD is 780 nm and from a DVD is 640nm. Assuming that the physical dimensions of the read-out mechanism for a CD and DVD are approximately the same, estimate the ratio of the depth of pit on CD compared to the depth of pit on DVD.

2 The wavelength used to read data from a DVD in a particular DVD player is 635 nm. Estimate the depth of the pits on the DVD.

## 14.1.6 (C.1.6) THE ADVANTAGES OF THE STORAGE OF INFORMATION IN DIGITAL RATHER THAN ANALOGUE FORM

The advantages of storing data in digital form as opposed to analogue form can be summarised as follows:

- quality and corruption
- reproducibility (accuracy)
- portability and high capacity
- manipulation

### Quality and corruption

Digital data is far less likely to be corrupted than analogue data. For example, if speech or music is stored on magnetic tape in analogue form, over time the magnetic field strength of the magnetised areas of the tape will decrease and the information will become blurred and indistinct. However, if the data is stored as regions of no magnetic field (0) and regions of magnetic field (1), even when the field reduces in strength, the distinction between 0 and 1 will still be readable.

### Reproducibility (accuracy)

When data is stored we often need to know where it stored in the storage device. Digital data enables an address to be given to each part of the storage system. Also, numeric data can be stored to a much higher degree of accuracy than analogue data (think abou tthe thermometer mentioned in 14.1.2). We have also seen that the same data can be retrieved over and over again without it being corrupted.

Storing alphabetic data in analogue form is fraught with problems not least in reproducing the data accurately. With digital storage, each letter of the alphabet and each punctuation symbol can be assigned a specific binary number. The digital code used is called the **ASCII code** - A(merican) S(tandard) C(ode for) I(nformation) I(nterchange).

## Portability and high capacity

As we have seen above, an enormous amount of information can be stored on CDs and DVDs. In computing, floppy discs that can store about 1 Mb have been replaced with "memory sticks" that can store up to 8 GB (at the time of publication). All of these devices can be easily slipped into a pocket or handbag.

## Manipulation

The fact that numeric information can be stored accurately in a digital form in elctronic calculators for example means not only that it is much easier to manipulate and process the data but the results of calculations should be less prone to error.

Also the fact that alphabetic data is easily stored in digital form means that the data can readily sorted and manipulated as in a database.

### 14.1.7 (C.1.7) THE IMPLICATIONS FOR SOCIETY OF EVER-INCREASING CAPABILITY OF DATA STORAGE

Clearly there are issues arising from the ever increasing amount of data that can be stored, and these issues are left for your teacher to raise during the teaching of this topic.

However, one issue in particular that your teacher might like to consider is the moral and ethical implications of the collection of personal data by Government and also by commercial organisations. Do the benefits (e.g. tracking down nefarious individuals and providing better consumer choice) outweigh the risks (e.g. loss of individual rights and the loss of privacy)?

In respect of commercial enterprises, the effect on the environment, of the increased paper output through advertising as well as the loss of privacy should also be considered. The scope for discussion is indeed wide.

# 14.2 (SL OPTION C.2) DATA CAPTURE; DIGITAL IMAGING USING CCDs

14.2.1 Define *capacitance*.

14.2.2 Describe the structure of a charge-coupled device (CCD).

14.2.3 Explain how incident light causes charge to build up within a pixel.

14.2.4 Outline how the image on a CCD is digitized.



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### 14.2.1 AND C.2.1 CAPACITANCE

In Topic 9.3 we learnt that the potential $V$ of a sphere of radius $r$ is which has a charge $Q$ is given by the expression

$$V = \frac{Q}{4\pi\varepsilon_0 r}$$

From this we see that the ratio $\frac{Q}{V}$ is equal to $4\pi\varepsilon_0 r$. This in effect means that the quantity of charge that can be stored per unit of potential of the sphere depends only on its geometry. This is in fact true for any system that can store electric charge and we call this property of the system **capacitance**. It is given the symbol $C$ and is defined as

$$C = \frac{Q}{V}$$

The SI unit of capacitance C $V^{-1}$ is called the farad (F). A device that is manufactured to have a specific capacitance is called a **capacitor**. A farad is an enormous unit and typical values of capacitance of commercial capacitors range from pF to several μF. To show just how large a unit the farad is, the capacitance of Earth is only about $10^{-1}$ F ($4\pi \times 8.85 \times 10^{-12} \times 6.4 \times 10^{6}$ ).

### 14.2.2 (C.2.2) THE STRUCTURE OF A CHARGE-COUPLED DEVICE (CCD)

A **charge-coupled device** (CCD) is a type of **complimentary metal oxide semiconductor** (CMOS) device. The principle of operation of the CCD is similar to the operation of a photodiode in which an electric potential difference is

generated by light liberating electrons from the valence band of a semiconductor (Topic 8.1.12). Figure 1405 shows the basic structure of a CCD.

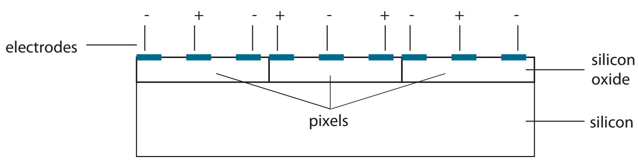


*Figure 1405 The basic structure of a CCD*

A layer of silicon dioxide about 5 μm thick is placed on the surface of silicon substrate about 500 μm thick. The silicon dioxide is divided into regions called **pixels**. Each pixel contains three electrodes. Each pixel essentially acts a capacitor.

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## 14.2.3,4 (C.2.3,4) PRINCIPLE OF OPERATION OF A CCD

What follows is just an outline of the operation of a CCD since the actual operation is quite complicated and requires a knowledge of solid-state physics that is beyond the level of the IB course.

When light is focussed on to the surface of the CCD, electron-hole pairs are produced in each pixel. Each photon of the incident light will produce one electron-hole pair such that the number of pairs produced will be proportional to the intensity of the light incident on the pixel. The electron pairs will migrate to the relevant electrodes resulting in a change in potential across the pixel.

It is this potential that is converted into a digital signal. At the same time, the position of each pixel is also recorded as a digital signal. In this way an intensity "map" of the surface of the CCD is built up. This intensity map is in effect an image of the "source" of the light focussed on to the CCD. The CCD is therefore acting like a piece of photographic film except of course, that in film the data is encoded in an analogue form.

An example will help to illustrate the principle of operation of the CCD.

Example

Suppose that a pixel has a capacitance of 40 pF and as the result of light incident on the pixel for a period of 30 ms, the change in potential across the pixel is 0.24 mV. Calculate the rate at which photons are incident on the pixel.

Solution

From $C = \frac{Q}{V}$ we have $Q = CV = 0.24 \times 10^{-3} \times 4.0 \times 10^{-11} = 9.6 \times 10^{-15}$ C

Number of photons = number of electrons produced

$$= \frac{9.6 \times 10^{-15}}{1.6 \times 10^{-19}} = 6.0 \times 10^{4}$$

Therefore number of photons per second

$$= \frac{6.0 \times 10^{4}}{3.0 \times 10^{-2}} = 2.0 \times 10^{6}\ \text{s}^{-1}.$$

14.2.5 Define *quantum efficiency* of a pixel.

14.2.6 Define *magnification*.

14.2.7 State that two points on an object may be just resolved on a CCD if the images of the points are at least two pixels apart.

14.2.8 Discuss the effects of quantum efficiency, magnification and resolution on the quality of the processed image.

14.2.9 Describe a range of practical uses of a CCD, and list some advantages compared with the use of film.

14.2.10 Outline how the image stored in a CCD is retrieved.

14.2.11 Solve problems involving the use of CCDs.



## 14.2.5-7 (C.2.5-7) QUANTUM EFFICIENCY, MAGNIFICATION AND RESOLUTION

### Quantum efficiency

In the foregoing example, we assumed that each photon that is incident on a pixel gives rise to an electron-hole pair. However, in practice some photons will be scattered by the surface of the CCD and some might reach the

silicon substrate without interaction with a valence electron in the silicon oxide. The percentage of photons in the incident light that produce electron-hole pairs is called the **quantum efficiency** and it is usually in the range 70-80%.

## Magnification

The magnification of a CCD is defined as the ratio of the length of image on CCD to the length of object.

## Resolution

The resolution of a CCD refers to the total number of pixels that there are in the image collecting area of the CCD. However, usually the resolution is defined in terms of the pixel array. So for example a CCD might be said to have a resolution of 1800 x 1600, that is the width of the image is collecting area is 1800 pixels wide and 1600 pixels in length. Alternatively it could be said to have a resolution of 2.88 megapixels (1800 × 1600).

It is worth mentioning that the human eye collects digital data and in this respect the retina has a resolution of about 11000 × 11000 or about 120 megapixel.

Although the number of pixels defines the resolution of a CCD, we still need to know how good a particular device is in actually resolving an image optically. For example if we use a digital camera to photograph a distance binary star system, will the CCD be able to resolve the two stars into separate images? Essentially, the answer is yes provided that the separation of the image of each star formed on the CCD is at least two pixels. If say, for a particular CCD, the pixel length is $1.5 \times 10^{-5}$ m, then for the binary star system, the two images on the CCD will just be resolved if they are separated by $3.0 \times 10^{-5}$ m.

## 14.2.8 (C.2.8) Quality of image

The greater the magnification of a given object, the greater will be the length of the image on the CCD and hence the greater the number of pixels that will be activated by the incident light. This means that the image will be more detailed. Also, the greater the resolution, the more pixels there will be in a given length so this in turn will produce a more detailed image.

The greater the magnification and the greater the resolution then the greater will be the resolving power of the CCD.

A word of warning here. Many digital cameras use what is called **interpolated resolution**. What this means is that software is used to add pixels to the final image, for example adding more "blue" pixels to the parts of the image that is blue. Although this process increases the overall file size, it does not add any further information to the image. This process is similar to that employed by the many photo-editing programs that are available. However, remember that the only way that you can get more detail from a CCD image is to physically increase the number of pixels on the CCD.

## 14.2.9 (C.2.9) Uses of CCDs

We have already alluded to one of the main uses of CCDs above, namely in digital cameras.

However, CCDs are used in a variety of other different imaging devices such as photocopiers, fax machines, mail sorters, and bar code readers. They are also used in closed circuit television cameras and in video cameras.

Perhaps one of their most dramatic uses has been in astronomy where there are used to detect very faint objects and therefore (usually) very distant objects. They have in fact been used in conjunction with the Hubble telescope to detect objects that are about $10^{11}$ times fainter than the brightest star (Sirius).

Coupled with the ability of CCDs to detect low levels of radiation, more recently they have been used to test how effective certain drugs are in binding to their target and they are now also used in X-ray imaging.

## 14.2.10 (C.2.10) Image retrieval

The following is a summary of image formation in a CCD and image retrieval:

- light from an object is brought to a focus on the collection area
- the light incident on the collection area varies in intensity and wavelength
- the number of electron ejected from each pixel will vary from pixel to pixel
- the potential change associated with each pixel varies from pixel to pixel
- the potential changes across the collection area is a "map" of the image of the object on the collection area
- each change of pd associated with a given pixel is converted to a digital signal

- the position of each pixel is recorded digitally
- these digital signals are converted to an image on an LCD screen (see 11.5.9/A.6.9)

In our discussion of CCDs we should bear in mind that we have not looked in any detail at the other parts of the imaging device. For example the device will have electronics that is used for image retrieval and also an optical system for focussing light on to the CCD. Furthermore, the pixels do not produce colour. In digital cameras, an array of colour filters is used to register the intensity of a single colour at each pixel. Software is then uses the intensities of colours at neighbouring pixels to estimate the intensity of the colour at a particular pixel.

Finally it has to mentioned that CCDs are likely to be soon supplanted by CMOS devices. The latter are much cheaper to produce and are also manufactured in much the same way as the integrated circuits used in modern microprocessors. However, the basic principles of image formation and retrieval are the same as that of a CCD.

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## 14.2.11 (C.2.11) SOLVE PROBLEMS INVOLVING THE USE OF CCDs

### Example 1

The collection area of a CCD used in a particular digital camera has an area of 30 mm × 30 mm. Each pixel of the CCD has an area of $2.2 \times 10^{-10}$ m$^2$. Estimate the resolution of the digital camera.

### Solution

$$\textit{number of pixels} = \frac{(3.0\times10^{-2})^2}{2.2\times10^{-10}} = 1.4 \times 10^6$$

*i.e. resolution = 1.4 megapixel.*

### Example 2

Light of wavelength 430 nm and intensity 1.4 mW m$^{-2}$ is incident on a pixel of area $2.2 \times 10^{-10}$ for 20 ms. The capacitance of the pixel is 25 pF. Calculate the change in potential difference across the pixel if the quantum efficiency of the CCD is 70%.

### Solution

*energy of photon*

$$= \frac{hc}{\lambda} = \frac{6.6\times10^{-34}\times3\times10^{8}}{4.3\times10^{-7}} = 4.6 \times 10^{-19}\ J$$

*number of photons per second per unit area*

$$= \frac{1.4\times10^{-3}}{4.6\times10^{-19}} = 3.0 \times 10^{15}$$

*number incident on pixel in 20 ms*

$$= 3.0\times10^{15}\times2.2\times10^{-10}\times 2.0 \times 10^{-2} = 1.3 \times 10^4$$

*number of electron-hole pairs produced*

$$= 0.7 \times 1.3 \times 10^4 = 9.1 \times 10^3$$

$$\textit{charge produced} = 9.1 \times 10^3 \times 1.6 \times 10^{-19} = 1.5 \times 10^{-15}\ C$$

$$\textit{using } C = \frac{Q}{V} \textit{ then } V = \frac{1.5\times10^{-15}}{2.5\times10^{-11}} = 0.038\ mV$$

### Exercises

1. A pixel has a capacitance of 40 pF. When illuminated for a short period of time, a change of potential of 0.20 mV is produced across the pixel. Estimate the number of electrons liberated from the valence band.

2. A CCD of a digital camera has an image collection area of 25 mm × 25 mm and a resolution of 5.0 megapixels. An object that is photographed by the camera has an area of $4.6 \times 10^{-3}$ m$^2$. The image area formed on the CCD is $1.0 \times 10^{-4}$ m$^2$.

   (a) Calculate the magnification.

   (b) Estimate the length of a pixel on the CCD.

   (c) Two small dots on the object are separated by a distance of 0.20mm. Discuss whether the images of the dots will be resolved.

3. Outline why, when the image area of a CCD is illuminated, the change in potential will vary from pixel to pixel.